

RETURN VOLTAGE MEASUREMENTS TO INVESTIGATE THE  
DEGRADATION OF ZINC OXIDE VARISTOR

ZULKARNAIN BIN AHMAD NOORDEN

A project report submitted in partial fulfilment of the  
requirements for the award of the degree of  
Master of Engineering (Electrical - Power)

Faculty of Electrical Engineering  
Universiti Teknologi Malaysia

NOVEMBER 2009

*Dedicated to my beloved parents*

*Ahmad Noorden and Rohaya*

*And my family*

*For their supports and blessings*

*To all my friends especially Siti Aisyah*

*For the emotional support throughout my ups and downs*

*All your kindness would not be forgotten*

## **ACKNOWLEDGEMENT**

First and foremost, the author would like to express his heartily, sincere gratitude to his supervisor, Associate Professor Dr. Zulkurnain bin Abdul Malek for the guidance and enthusiasm given throughout the progress of this project. His appreciation also goes to his family who has been so tolerant and always supports him in completing this project. Thanks for their encouragement, love and emotional support that they had given to him. Finally, his great appreciation dedicated to his colleagues, Mr. Aulia and Mr. Novizon, as well as to all IVAT staff for their contributions either on technical or non-technical aspects of the project. Thank you very much.

## ABSTRACT

Due to their reliability and accuracy, many modern diagnostics based on dielectric voltage response, such as polarization/depolarization current (PDC), voltage decay (VD) and return voltage (RV) measurements, have been used in monitoring ageing processes of metal oxide (MO) varistors. Among these diagnostics, recently, RV measurement (RVM) seems to be an increasingly popular method as it has high sensitivity to the condition of varistors and low sensitivity to disturbances in vicinity of the field measurements. Nonetheless, the basic interpretation based on the RVM essential parameters – peak RV, time-to-peak RV and initial slope of RV - provides insufficient information of the MO varistors condition since they are inevitably dependent on the measuring parameters such as the charging and discharging times as well as the test object temperature. Hence, this project focuses on a new way in interpreting the RVM parameters based on dielectric time constants analysis using an equivalent circuit of varistor microstructure, namely the Maxwell-Model. In order to investigate the ageing processes of MO varistors, two types of accelerated degradation techniques – impulse and heat degradations – are systematically conducted on test samples. Experimental results are presented and discussed in detail according to the underlying physical mechanism. On the basis of this concept, a sensible ageing parameter, *p-factor*, is used for better characterization of the ageing status of varistors.

## ABSTRAK

Disebabkan oleh keboleharapan dan ketepatannya, banyak diagnostik moden berdasarkan pada respon voltan dalam dielektrik, seperti pengukuran pengutuban/penyahkutuban arus (PDC), voltan penyusutan (VD) dan voltan balikan (RV), telah digunakan dalam proses pemantauan penuaan varistor oksida logam (MO). Di antara diagnostic-diagnostik ini, kini, pengukuran RV (RVM) semakin meningkat digunakan kerana mempunyai kepekaan yang tinggi terhadap keadaan varistor dan sensitiviti rendah terhadap gangguan persekitaran proses pengukuran. Walaubagaimanapun, penguraian asas berdasarkan pembolehubah penting RVM - puncak RV, masa-ke-puncak RV dan kecerunan awal RV - tidak memberi maklumat yang cukup tentang keadaan varistor MO kerana ia bergantung pada parameter pengukuran seperti tempoh pengecasan and penyahcasan serta suhu objek. Oleh kerana itu, projek ini fokus pada cara baru dalam mengurai pembolehubah RVM berdasarkan analisis pemalar dielektrik masa dengan menggunakan litar yang sesuai untuk varistor mikrostruktur - Maxwell-Model. Dalam proses untuk menyiasat penuaan varistor MO, dua jenis teknik penuaan – secara aplikasi dedenyut dan pemanasan - dilakukan secara sistematik pada sampel. Keputusan eksperimen tersebut dilaporkan dan dibincangkan secara terperinci sesuai dengan mekanisme fizikal yang mendalam. Atas dasar konsep ini, pembolehubah yang sesuai, *p-faktor*, digunakan untuk menggambarkan dengan lebih baik status penuaan varistor.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	x
	<b>LIST OF FIGURES</b>	xi
	<b>LIST OF SYMBOLS</b>	xiii
	<b>LIST OF ABBREVIATIONS</b>	xv
<b>1</b>	<b>INTRODUCTION</b>	1
	1.1 Project Background	1
	1.2 Problem Statement	2
	1.3 Objective of Project	3
	1.4 Scope of Project	3
	1.5 Thesis Outline	3
<b>2</b>	<b>LITERATURE REVIEW</b>	5
	2.1 ZnO Varistor as Overvoltages Protective Device	5
	2.1.1 Introduction	5
	2.1.2 Microstructure and Common Equivalent Circuit of ZnO Varistor	6
	2.1.3 Electrical Characteristics of ZnO Varistor	7
	2.1.4 Principle of Operation of ZnO Varistor	8
	2.2 Degradation and Failure Mode of ZnO Varistor	9

2.2.1	Electrical and Thermal Stresses	10
2.2.2	Failure Mode	11
2.3	ZnO Varistor Diagnostic Technique using Return Voltage Measurements Method	11
2.3.1	Introduction	11
2.3.2	Return Voltage Measurements as a Reliable Diagnostic Technique for ZnO-based Protective Device	12
2.3.2.1	Basics of Return Voltage Measurements Phenomenon	12
2.3.2.2	Previous Researches of Return Voltage Measurements on Insulation System	14
<b>3</b>	<b>METHODOLOGY</b>	<b>16</b>
3.1	Modeling ZnO Varistor based on Return Voltage Measurements Phenomenon	16
3.1.1	Common Model of ZnO Varistor	16
3.1.2	Modeling ZnO Varistor based on Maxwell-Model	17
3.1.3	Evaluation of Maxwell-Model Circuit	18
3.2	Laboratory Studies on ZnO Varistor Degradation	20
3.2.1	Test Sample Selection	20
3.2.2	Return Voltage Measurements	22
3.2.3	Total Leakage Current Measurements	24
3.2.3	1 mA Reference Voltage Measurements	26
3.2.4	Artificial Degradation of ZnO Varistor	27
3.2.4.1	Impulse Degradation	27
3.2.4.2	Heat Degradation	30
3.3	Interpretation of Return voltage Measurements	31
3.4	Project Flow Chart	32
<b>4</b>	<b>RESULTS AND DISCUSSION</b>	<b>34</b>
4.1	Introduction	34

4.2	Results of Return Voltage Measurements	34
4.2.1	Sample A – Impulse Degradation	34
4.2.2	Sample B – Heat Degradation	36
4.2.3	Sample C – Impulse Degradation	38
4.2.4	Sample D – Heat Degradation	40
4.3	Results of Total Leakage Current Measurements	42
4.4	Results of 1 mA Reference Voltage Measurements	44
4.5	Results Comparison	45
<b>5</b>	<b>CONCLUSION</b>	<b>48</b>
5.1	Conclusion	48
5.2	Recommendation	49
	<b>REFERENCES</b>	<b>50</b>
	Appendices A - C	54



**LIST OF TABLES**

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
3.1	Specifications of Samples	21
3.2	Artificial Degradation Works for All Samples	27
4.1	Results of Total Leakage Current Measurements	43
4.2	Results of 1 mA Reference Voltage Measurements	44
4.3	Results Comparison between RVM, Total Leakage Current and 1 mA Reference Voltage Measurements	46

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Microstructure of ZnO Material	6
2.2	Simple Equivalent Circuit of ZnO Material	7
2.3	Typical V-I Characteristics Curve of MO Varistor on a Linear Scale, using Sample from Manufacturer	8
2.4	MOV Operation (a) Under Normal Operating Voltage and (b) Under Overvoltage Condition	9
2.5	Arrangement of Return Voltage Measurement	13
2.6	Return Voltage Cycle	13
3.1	Common Equivalent Circuit of ZnO Material for RVM Phenomenon	17
3.2	Maxwell Equivalent Circuit for ZnO Material	18
3.3	Voltages across the capacitors $C_1$ and $C_2$ (Figure 3.2) during RVM	19
3.4	(a) Block-type, and (b) Radial Leaded-type Varistors	20
3.5	Automatic Recovery Voltage Meter Type RVM5462	23
3.6	Experimental Setup of RV Measurements	23
3.7	Circuit Diagram of RV Measurements	24
3.8	Experimental Setup of Total Leakage Current Measurements	25
3.9	Circuit Diagram of Total Leakage Current Measurements	25
3.10	Computer-Connected Picoscope	25
3.11	Voltage and Current Waveforms of a Sample During 1 mA Reference Voltage Measurement	26
3.12	Combination Impulse Waveshapes Generator, HAEFELY PSURGE30	28

3.13	Impulse Degradation Experimental Setup	29
3.14	An example of Lightning Combination Oscillograms Used for Impulse Degradation	29
3.15	Digimatic Drying Oven	30
3.16	Relationship Between $p$ -factor and $\lambda$	32
3.17	Flow Chart of Project	33
4.1	Peak RV, RV Initial Slope and Time-to-Peak RV Plots For Sample A	35
4.2	Relationship Between $p$ -factor and $\lambda=\tau_2/\tau_1$ for Sample A	36
4.3	Peak RV, RV Initial Slope and Time-to-Peak RV Plots For Sample B	37
4.4	Relationship Between $p$ -factor and $\lambda=\tau_2/\tau_1$ for Sample B	38
4.5	Peak RV, RV Initial Slope and Time-to-Peak RV Plots For Sample C	39
4.6	Relationship Between $p$ -factor and $\lambda=\tau_2/\tau_1$ for Sample C	40
4.7	Peak RV, RV Initial Slope and Time-to-Peak RV Plots For Sample D	41
4.8	Relationship Between $p$ -factor and $\lambda=\tau_2/\tau_1$ for Sample D	41
4.9	Total Leakage Current Measurements for Sample D	42
4.10	Chart of Slope of Total Leakage Current Measurements for All Samples	43
4.11	Chart of 1 mA Reference Voltage Measurements for All Samples	45
4.12	Charts of Comparison for Each Technique for All Samples	47

## LIST OF SYMBOLS

$R_{IG}$	-	Resistance of intergranular layers
$C_{IG}$	-	Capacitance of intergranular layers
$R_{GRAIN}$	-	Resistance of grains
$I$	-	Current
$K$	-	Ceramic constant
$V$	-	Voltage
$\alpha$	-	Non-linearity exponent
$S1$	-	Switch 1
$S2$	-	Switch 2
$U_p$	-	Charging voltage
$t_c$	-	Charging time
$t_d$	-	Discharging time
$U_m$	-	Peak return voltage
$t_m$	-	Time to reach return voltage
$s$	-	Initial slope of return voltage
$R_o$	-	Geometric resistance
$C_o$	-	Geometric Capacitance
$R_{ns}$	-	Resistance of n-th parallel branches
$C_{ns}$	-	Capacitance of n-th parallel branches
$\epsilon_r$	-	Relative permittivity
$\rho$	-	Specific resistance
$\tau_1$	-	Dielectric time constant of material 1
$\tau_2$	-	Dielectric time constant of material 2
$C_1$	-	Capacitance of material 1
$C_2$	-	Capacitance of material 2
$\epsilon_1$	-	Permittivity of material 1
$\epsilon_2$	-	Permittivity of material 2

$R_1$	-	Resistance of material 1
$R_2$	-	Resistance of material 2
$\rho_1$	-	Specific resistance of material 1
$\rho_2$	-	Specific resistance of material 2
$R_L$	-	Resistor of current limiter
$V_{HV}$	-	Voltage on high voltage arm
$V_{LV}$	-	Voltage on low voltage arm
$^{\circ}C$	-	Degree Celsius
$\tau$	-	Dielectric time constant
$U_r$	-	Return voltage
$U_s$	-	Voltage after short circuit period
$p\text{-factor}$	-	New ageing parameter

## LIST OF ABBREVIATIONS

UTM	-	Universiti Teknologi Malaysia
IVAT	-	Institute of High Voltage and High Current
ZnO	-	Zinc oxide
MOV	-	Metal oxide varistor
MO	-	Metal oxide
MOSA	-	Metal oxide surge arrester
VD	-	Voltage decay
PDC	-	Polarization/Depolarization current
RV	-	Return voltage
RVM	-	Return voltage measurement
V-I	-	Voltage-current
DC	-	Direct current
MCOV	-	Maximum continuous operating voltage
rms	-	Root mean square
Hz	-	Hertz
mm	-	Millimeter
kA	-	Kilo amperes
kV	-	Kilo volts
$\mu$ s	-	Micro second
pF	-	Pico farad
J	-	Joule

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Project Background**

Surge protection devices are often used to protect power and electronic equipment from the destructive transient overvoltage from lightning or other large-magnitude surge. These devices are used to limit the overvoltage to a level which is sufficiently safe for the equipment being protected by diverting the large current to ground. The non-linearity characteristics of these devices depend on their material composition. One type of non-linear devices is known as metal oxide varistor (MOV). MOV is a ceramic device with highly non-linear electrical characteristics; similar to those of a back-to-back diode, and has been used for low voltage application (below 1 kV). For higher voltage application that is above 1 kV the protection device is usually known as metal oxide surge arrester (MOSA) which may consists of several MOV blocks. Due to its high nonlinear characteristics, these devices have high energy absorption capability which is a good characteristic for an overvoltage suppressor.

However, these nonlinear characteristics can be degraded by the effects of electrical and thermal stresses as well as chemical reactions with the surrounding material. Usually, the thermal stress is considered as effect due to the temperature rise of the metal oxide materials subsequent to the discharge of high energy surges. While, the electrical stress may be the effects of voltage stress by its own operating

voltage at ambient temperature or by high current stress due to overvoltages occurrence.

In the past, many investigations of several non-destructive diagnostic techniques have been conducted for reliable condition assessment of the ageing of MOSA. These diagnostic techniques include the standard 1mA reference voltage, lightning impulse discharge residual voltage, voltage decay (VD), polarization or depolarization current (PDC) and Return Voltage (RV) measurements. The modern diagnostic techniques based on dielectric response such as VD, PDC and RV measurements, have also been used to evaluate insulating materials such as cables and transformers [1-4].

Among these modern diagnostic techniques, recently, the return voltage measurement (RVM) seems to be increasingly used as a reliable diagnostic method in monitoring the ageing process of the metal oxide materials due to its high sensitivity to smaller degrees of degradation [5]. In addition, RVM has low sensitivity to disturbances by external noise, a situation that is auspicious for in-field measurements [6].

## **1.2 Problem Statement**

RVM method is a good approach to attain the information of insulating components condition for devices such as ZnO varistor (under normal operating mode). Due to less sensitive to disturbances, the measurements are reliable and also reproducible, at least with regard to the collection of the data. Unfortunately, in the past, not all RVM interpretation methods suggest correct insulation components condition information because of unreliable diagnosis parameters and inaccurate RVM data interpretation approach. Hence, this project focus on investigation of an accurate and correct way to interpret RVM data of ZnO varistor in order to obtain real physical condition of the ZnO insulation.



### **1.3 Objective of Project**

There are two main objectives that have been achieved in this project:

- To model the equivalent circuit of ZnO varistor according to RVM phenomenon using Maxwell multilayer dielectric circuit.
- To investigate reliable interpretation of ZnO degradation process using RVM method.

### **1.4 Scope of Project**

The main scope of this project is to study the diagnostic technique of ZnO varistor based on RVM method which includes:

- Study of behaviour and characteristics of metal oxide material;
- Study of theory, principles and interpretation of RVM;
- Evaluation of metal oxide material using multilayer dielectric approach – Maxwell-Model;
- Experimental works of ageing investigation on MOV using RVM method; and
- Results validation by comparison with total leakage current and 1 mA reference voltage measurements.

### **1.5 Thesis Outline**

This thesis is divided into five chapters. Generally, some basic principles, theories, equations, previous researches' references, experimental result and discussions are discussed included in these chapters based on the contents requirements of each chapter.

In chapter 1, the author has included the project overview and the main objectives of conducting this project. Chapter 2 presents some background information of the project, such as the description of ZnO varistor as overvoltage protective device, and RVM as ZnO varistor diagnostic technique. This chapter briefly explains the ZnO varistor structure, common equivalent circuit and electrical characteristics as well as the importance of conducting a research on its diagnostic technique. At the end of the chapter, the author summarizes the current research works done by other researchers and of course their valuable recommendations.

Chapter 3 presents the methodologies of modeling ZnO varistor as well as the experimental procedures of carrying out the RV measurements. These are presented in a flow chart form together with a brief explanation. The RVM interpretation methods are discussed at the end of this chapter. Then, results and discussion are covered in Chapter 4.

Finally, Chapter 5 summarizes all the works and studies that had been presented in the previous four chapters. Besides, some future works are recommended at the end of the chapter.